



Assessment of the devolatilization behavior of fuel pellets in fluidized bed



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ABSTRACT

The volatile release or devolatilization is an early stage occurring upon fuel particle feeding in a combustor. For coarse fuel particles, as in the case of fluidized bed (FB) combustion, it is mainly controlled by the thermal properties of the bed and fuel. The direct observation of the particle behavior in fluidized bed is a simple and effective technique for getting information on the devolatilization time and the number of volatile bubbles issuing from the fuel particle. The paper reports on experiments of devolatilization of different fuel particles of similar size, with particular concern on pellets composed by wood and wood/coal. The experimental technique was mainly based on the visual observation of the bed surface, the data-acquisition by a video-camera and the post-process elaboration of the frame sequences. Devolatilization times of dozens of seconds were measured for pelletized fuels, longer than those of normal wood particles. Two kinds of events were observed during devolatilization: i) the eruption of a “hot bubble” produced by bursting a submerged fuel-rich bubble, ii) the generation of “flames” at the bed surface. The number of such events was counted, obtaining values up to 100 per single particle under more critical conditions. A correlation between the number of monitored events and a dimensionless variable – function of FB and fuel properties – was proposed, providing a reasonable dependence on most relevant variables.

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1. Introduction

The fluidized bed (FB) technology is considered to be flexible and reliable for thermo-chemical processing of fossil and biogenic fuels, including combustion, gasification and pyrolysis [1]. Fluidized bed also boasts very large heat transfer coefficients. Fuels with wide range of particle size and moisture content are suitable for FB application. Upon feeding into a hot fluidized bed, a fuel particle undergoes a series of stages from the initial release of the moisture to the final transformation into ashes [2]. Among such stages, the devolatilization occurs after moisture release (drying) in a temperature range 200–600 °C, depending on the fuel nature. During devolatilization, the organic volatile matters gradually leave the particle, which is transformed into a porous light char. The devolatilization is an endothermic step, needing heat from the external environment. It can be either thermally or kinetically controlled [3], depending on particle size and shape [3,4]. In the case of FB process, the devolatilization is under thermal control, by virtue of the substantially large fuel particle size. Finally, the released volatiles undergo a complex pattern of chemical reactions including cracking and reforming steps, before final oxidation [5].

The enthalpy of devolatilization or pyrolysis (ΔH_d) is a characteristic property that depends on the fuel nature but also on the particle heating rate. Experimental data from TG-DSC tests [6] were in the range 0.2–

0.5 MJ/kg for spruce and beech wood pyrolysis. Reed and Cowdery [7] proposed an estimating equation of ΔH_d accounting for the char fraction generated upon pyrolysis. Congruently, increasing the heating rate and temperature leads to a larger volatile yield and, in turn, higher enthalpy of pyrolysis [8]. In real conditions, e.g. a fluidized bed, the enthalpy of pyrolysis can be significantly higher than values obtained in thermo-gravimetric tests. Dugaard and Brown [9] estimated values in the range 0.7–1.7 MJ/kg for different biomass fuels (i.e. oak, pine, corn stover) in a dedicated equipment based on the FB concept. Since the coal pyrolysis produces a higher char yield than biomass, the enthalpy for pyrolysis is correspondingly smaller. It is worth recalling that the devolatilization can be accompanied by the parallel occurrence of the primary fragmentation, leading to generation of multiple fragments [2]. In this case, the total time required for the devolatilization decreases, because of the dependence on the mean particle size and exposed surface.

The bubbles issuing from a fuel particle during the devolatilization, so called “endogenous” bubbles following Fiorentino et al. [10], climb up the bed and erupt at the surface where they burn-off. The volatile release is also responsible of fast and stable fuel particle segregation at the bed surface, at least in conditions of incipient bubbling regime [11]. The direct observation of the particle behavior in fluidized bed provides information on the devolatilization time and bubble associated phenomena. For particles having typical size for fluidized bed application, the devolatilization time is in the range 10–40 s, whereas the number of observed volatile bubbles is largely variable depending on

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the nature of the fuel and the parallel onset of coalescence phenomena [12] between bubbles. The number of bursting bubbles at bed surface was reported in the range 2–12 by Fiorentino et al. [10] for three fuels, namely wood chips, bituminous coal and TDF, in a hot bed (550–850 °C) at minimum fluidization. It is worth noting that these values account only for bubbles produced during the rising time of the “free particle” that is substantially lower than the whole devolatilization time.

Nowadays, there is a growing interest toward the pelletization of biomass fuels and residues as useful measure for increasing the bulk density and for improving the fuel properties [13]. Benefits of the pelletization can be particularly appealing at small scale application, thanks to simpler handling and metering fuel devices. Chirone et al. [14] investigated the FB combustion of three different fuel pellets, reporting some advantages with respect to the original loose fuels: longer devolatilization time, very low primary fragmentation, moderate attrition, high efficiency. The devolatilization and comminution of coal and wood pellets were recently addressed by Ammendola et al. [15]. They observed that no significant primary fragmentation occurs during devolatilization in fluidized bed for both commercial and home-made pellets, whereas the attrition is strongly dependent on parent fuel used for making the pellets.

This research is a contribution in understanding the pellet behavior during devolatilization, with particular focus on the endogenous bubbles generated during this stage under conditions of freely-bubbling fluidized bed. The experimental technique was mainly based on the visual observation of the bed surface, the data-acquisition by a video-camera and the post-process elaboration of the frame sequences, for identifying over-bed flames and bubble bursting inside the bed. The paper reports and discusses the experimental results in terms of devolatilization time and number of volatile bubbles for wood and wood + coal pellets with respect to wood particles.

2. Materials and methods

2.1. Apparatus for devolatilization

The experimental apparatus for determining the particle behavior during devolatilization stage is schematically shown in Fig. 1-A. It is a

120 mm ID, 500 mm high fluidized bed, which is heated by means of an external electric furnace. The fluidization column is open in the top side, allowing the visual observation of the bed surface. A fixed bed of 3/8" stainless steel balls serves as gas distributor in the bottom. A mass-flow meter is used for measuring the air flow rate for fluidization, whereas the bed temperature T is measured with a submerged thermocouple.

The bed material was silica sand having two average sizes: 325 μm (fine) and 600 μm (coarse). The bed was kept under bubbling fluidization regime with a total expanded height of about 250 mm. The bed temperature T was fixed at two different levels: 690–700 and 760–770 °C. The fluidization velocity U was 0.11 m/s (fine sand) and 0.21 m/s (coarse sand), corresponding to equal excess of fluidization velocity $U - U_{\text{mf}} = 0.06$ m/s.

The basic technique, referred to as “free pellet”, for fuel feeding consists in throwing a pellet from the top. In alternative, a cage, displayed in Fig. 1-B, was used for introducing a single pellet at fixed bed elevation or, in other words, at fixed depth below the bed level, keeping it in that position during the whole test. The depth Δz was kept at three discrete values, i.e. 50, 70, 80 mm.

2.2. Data acquisition and processing

A digital video-camera was used for recording the image of the top view during each test, with resolution 640×480 pixels. Post processing of the acquired frame sequences was accomplished by means of the free software “VirtualDub” by Avery Lee that enables to inspect the movies frame by frame and to apply several filters. The movies were visually inspected in order to trace the phenomena occurring in the bed (see below).

Alternatively, the frame sequence obtained by each recorded movie was processed by a purposely developed software tool for determining the ratio Y of pixels in a single frame having luminosity λ higher than a given threshold λ_t . The luminosity was calculated as the sum of the red, green and blue components (1 byte) in the pixel, yielding a value between $\lambda = 0$ (black) and $\lambda = 765$ (white). A typical threshold adopted for processing is $\lambda_t = 255$, corresponding to the dominant red components.

Table 1
Properties of parent fuels and pellets.

Parent fuel	Beech wood	Spruce wood	German brown coal	Polish coal
LHV, MJ/kg daf	17.4	18.5	24.1	31.0
<i>Proximate analysis</i>				
Moisture, %	9.1	8.4	18.7	7.7
Fixed C, %	15.0	17.1	36.6	54.9
Volatiles, %	75.6	74.2	41.7	28.8
Ash, %	0.3	0.3	3.0	8.6
<i>Ultimate analysis (daf)</i>				
C, % daf	49.2	49.4	67.9	79.1
H, % daf	6.1	5.9	5.1	4.5
S, % daf	<0.1	0.1	0.5	0.5
N, % daf	0.3	0.1	0.8	1.3
Cl, % daf	<0.1	<0.01	0.06	0.4
O, % daf	44.1	44.4	25.7	14.2
Average devolatilization temperature, °C	345	340	410	500
Devolatilization enthalpy, kJ kg^{-1}	192	210	160	150
<i>Particles</i>				
Type	Beech rod	Spruce pellet	GBC30 pellet	PC30 pellet
Diameter, mm	6	6	6	6
Length, mm	10–15	10–15	10–15	10–15
Composition	100% beech	100% spruce	30% German coal + wood	30% Polish coal + wood
Moisture	9.1	8.4	8.4	6.8
Density	779	1150	1200	1160

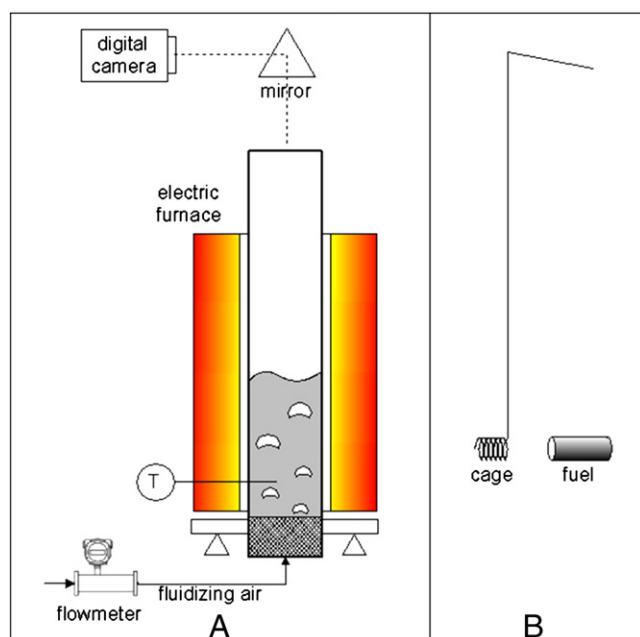


Fig. 1. The experimental FB apparatus 120 mm ID (A) and the cage for the fuel particle (B).



Fig. 2. Fuel pellets used for the experiments A: beech rods; B: spruce pellets; C: GBC pellets; D: PC pellets.

2.3. Fuels

Dried beech rods, commercial wood pellets (spruce) and purposely made wood-coal pellets were used for the experiments. Two different coals were considered: German brown coal (GBC) and Polish bituminous coal (PC) with a coal/wood mass ratio equal to 30/70. The properties of the parent fuels and pellets are reported in Table 1, where the

reported average temperature and enthalpy of devolatilization were estimated by TG-DSC analyses. Both woods (beech and spruce) have very similar volatile contents that are significantly higher than the GBC and PC values. The moisture of the final particles is limited to the inherent water content (<10% by weight), since the pelletization takes place with concurrent heating of the processed materials. Photographs of the fuel particles are shown in Fig. 2.

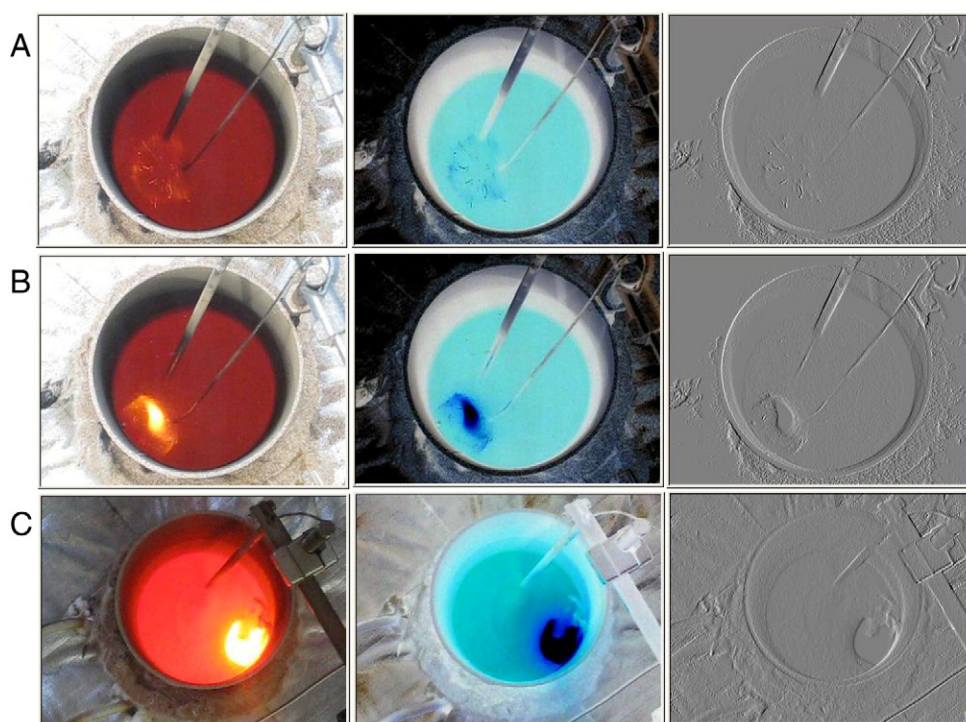


Fig. 3. Frames obtained by video-recording the bed surface during the devolatilization of a single pellet (1st col. no filter, 2nd col. invert filter, 3rd col. emboss filter). A) "hot bubble" – GBC pellet in cage. B) "flame" – GBC pellet in cage. C) "flame" – GBC free pellet.

3. Results and discussion

3.1. Qualitative aspects

Fig. 3 shows three frames obtained during the devolatilization of a single pellet (GBC). Both frames A and B refer to a test with “cage”, whilst the frame C to “free pellet”. For each recorded frame, invert and emboss filters were applied to highlight the phenomena under observation. In general, upon a short delay from pellet feeding, smoke and flames were issued during the entire devolatilization time, lasting dozens of seconds. There was no evidence of occurring primary fragmentation during the devolatilization of all three kinds of pellets (“free pellet” and “cage” technique). Multiple fragments were produced in limited cases at late stage of conversion, as consequence of secondary fragmentation. In that case, they escaped the cage and appeared at bed surface.

From the analysis of the frame sequences, two kinds of events can be distinguished: i) the eruption of a “hot bubble” produced by bursting a submerged fuel-rich bubble, ii) the generation of “flames” at the bed surface upon ignition of fuel vapors that escape the bed. The first event is shown in Fig. 3-A for the cage technique; the second event is displayed in Figs. 3-B and -C, for both adopted techniques.

The analysis of the frames obtained with “free pellet” shows that the fuel particle stably remains over the bed surface during the devolatilization step, confirming the well known results of particle segregation [10]. Therefore, the observed events were limited in this case to flames only.

In general, the size of the area covered by the “hot bubble” and “flame” events is in the range 3–6 cm. More specifically, PC pellets, having the lowest content of volatiles, gave rise to smaller and less detectable events.

3.2. Devolatilization time

It was assumed that the devolatilization time t_{dev} is that of the last observed event, although residual volatiles would be slowly released during the late devolatilization stage [15]. Accordingly, the assumed t_{dev} is representative of the interval during which the emission of volatiles occurs. If t_{dev} is small, the rapid release of volatile matters promotes undesirable segregation phenomena, i.e. the formation of bubbles rich in volatiles that bypass the bed and erupt in the freeboard. A rapid devolatilization also forces the fuel particle to stay segregated at the bed surface [10].

The measured values of the devolatilization time obtained with spruce, GBC, PC pellets and beech rods are shown in Fig. 4, for “cage” at $T = 770$ °C. The measurements were repeated twice and the values are reported as distinct columns in the figure. The devolatilization times ranged between 20 and 41 s. The trend of t_{dev} reported in Fig. 4 is consistent with the volatile mass contained in the fuel particles

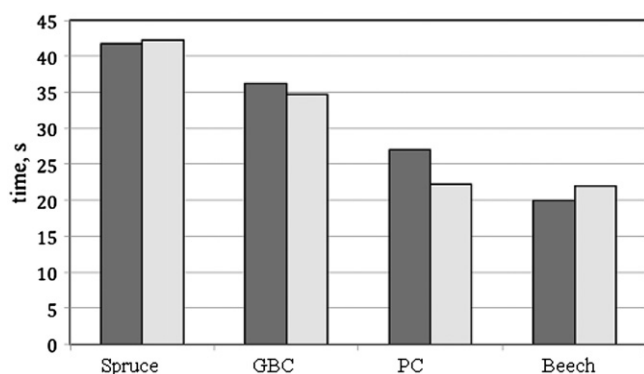


Fig. 4. Devolatilization time for Spruce, GBC, PC pellets and beech rods (770 °C, “cage”, fine sand, two repetitions).

(spruce > GBC > PC > beech), which increases with both particle density and volatile content. These results are comparable with those by Sreekanth et al. [16] obtained for hard wood by using a basket in a fluidized bed at 850 °C. In that case, 10 mm fuel particles gave a devolatilization time of around 50 s that is congruently larger than current values, because of the coarser particle size.

It is worth noting that almost twice the devolatilization time is required passing from natural wood (beech) to pelletized wood (spruce), as consequence of the larger particle density. It was also observed that t_{dev} increases when the fuel particle floats over the bed surface (“free pellet”), as consequence of the reduced surface of heat transfer between the pellet and the bed. However, the benefit of a longer devolatilization time is contrasted by the direct release of volatiles into the freeboard, and the associated bypass of the bed.

3.3. Quantification of flames and hot bubble events

The time evolution of “flame” and “hot bubble” events is displayed in Fig. 5, for spruce and GBC pellets in fine sand at 770 °C. Two curves obtained by visual inspection frame by frame of the recorded movies under the same experimental conditions are reported in the figure for both tested fuels. Under such conditions, the number N_b of “hot bubble” already exceeds that (N_f) of “flame” events. In general, the event distribution is rather uniform during the entire devolatilization time, but the flame events are more frequent at the beginning, indicating that the volatiles are initially released at larger rate. In the late stage it is likely that the produced bubbles are enriched in CO, explaining the decay of

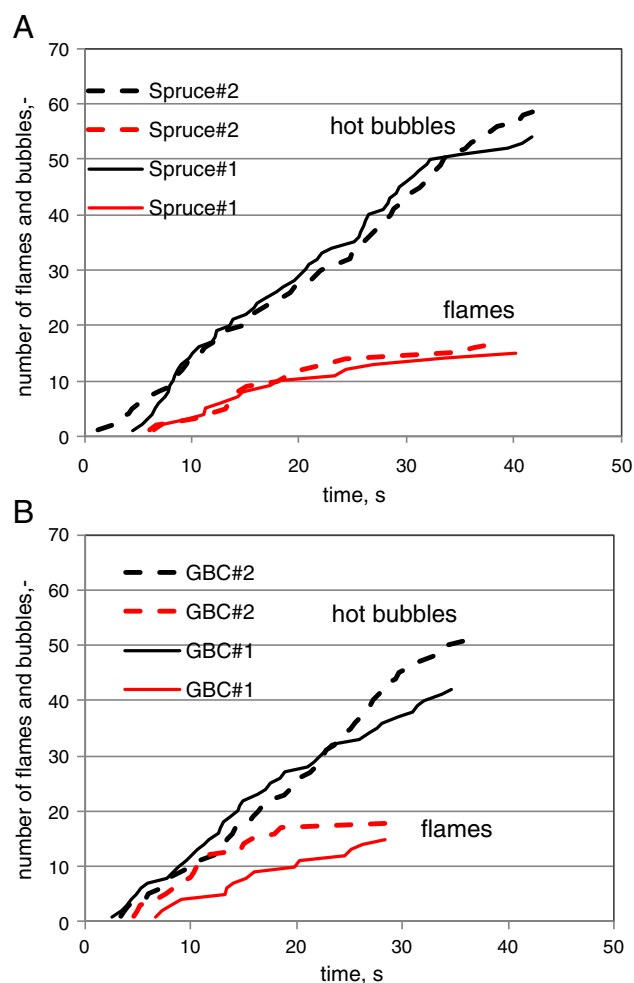


Fig. 5. Number of “hot bubbles” and flames for pellets in cage (fine sand, $T = 770$ °C). A) Spruce, B) GBC.

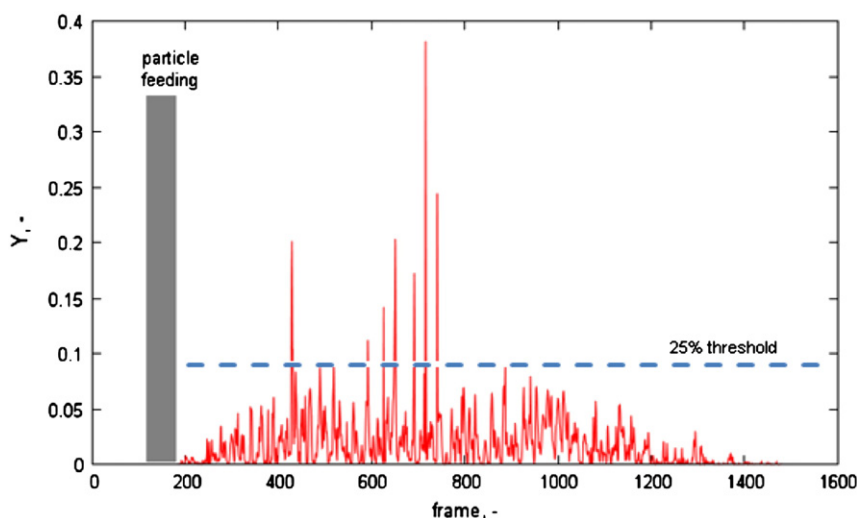


Fig. 6. Time diagram of the luminosity index (spruce, fine sand, $T = 750\text{ }^{\circ}\text{C}$).

flaming events, since the CO emission during fuel pyrolysis increases at higher particle temperature [17]. This particularly applies for coal based pellets.

The results of software post-processing allowed obtaining more detailed information on the events occurring during particle devolatilization. Fig. 6 displays the typical diagram from elaboration of a movie in terms of luminosity index Y . The test conditions are: spruce pellet, fine sand and $T = 750\text{ }^{\circ}\text{C}$. A peak appears in the diagram when a luminous event is registered, whose height depends on the extent of the bright surface (number of pixels) with respect to the total surface. The time series of peaks is very dense in the middle region (400–1200 frames) that corresponds to the time after the particle feeding, initial heating and drying. In the last region of the diagram a decay of the registered events clearly appears.

Fig. 7 displays a diagram similar to that of Fig. 6 and obtained at $T = 700\text{ }^{\circ}\text{C}$. The number and height of peaks are significantly lower than shown in Fig. 6, indicating that the bursting events are infrequent and less intense as a consequence of the lower temperature.

The intensity of Y peaks allows discriminating between “flame” and “bubble” events. A calibration was done by comparing the visual analysis and the software elaboration; it was found that a suitable threshold

is 25% of the largest peak registered in the diagram. Furthermore, small peaks that are very close to the baseline were neglected. Thus, the examination of each diagram enables determining the number of both “flame” and “bubble” events, indicated as N_f and N_b , respectively. The sum of N_f and N_b , gives the total number of events N_e . The error in estimation of the number of events is around 10% as consequence of disturbance caused by spurious phenomena (e.g. random presence of small and incandescent char fragments) during the software elaboration.

The numbers N_b , N_f , N_e are reported in Table 2 as obtained from the visual or, alternatively, software examination of the recorded movies. It is evident that there is a correlation between the volatile content (spruce & beech > GBC > PC) and the devolatilization time: a higher volatile content leading to a larger number of gaseous bubbles that ignite inside the bed or erupt at its surface. In parallel, an influence of the explored variables, namely T , d_s and Δz , can be noted from the analysis of the data. As expected, there is a dominant influence of the particle depth Δz , the number of observed events being increased at smaller Δz , as shown in Fig. 8-A reporting selected data points of Table 2. The dependence on temperature is not straightforward: tests carried out at similar conditions exhibit an increase of detected events with T (Fig. 8-B), but the minimum number of events was

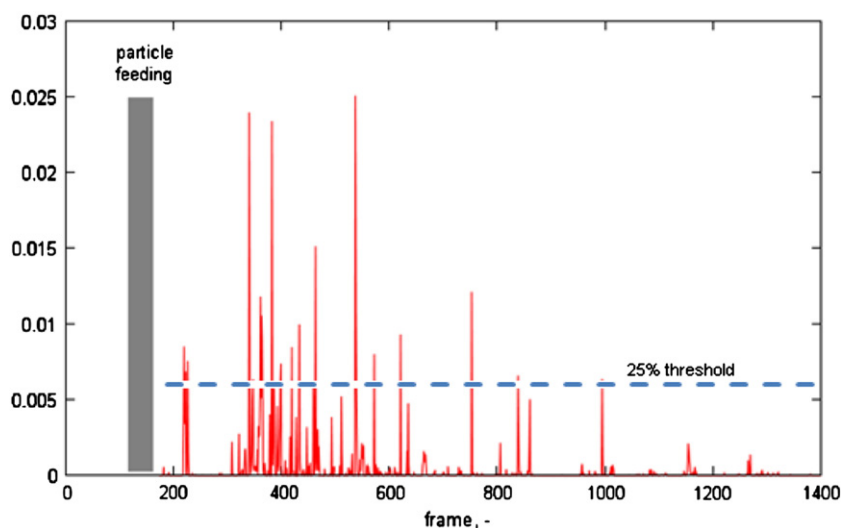


Fig. 7. Time diagram of the luminosity index (spruce, fine sand, $T = 700\text{ }^{\circ}\text{C}$).

achieved in coarse bed at the highest temperature and greatest depth. Furthermore, the tests carried out at the lowest temperature in coarse bed and minimum Δz gave rise to the highest N_e , approximately 100 events per particle.

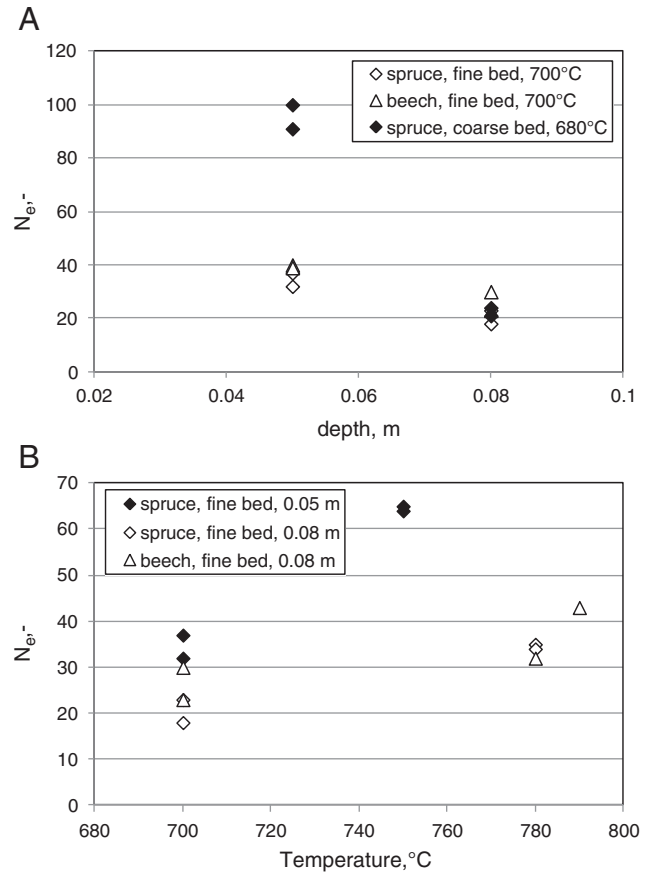
Fig. 9 shows the comparison between the number of flame and bubble events for spruce pellets. Again, there is a marked influence of the particle depth: N_f exceeds N_b at $\Delta z = 5$ cm, whilst the situation is reversed at $\Delta z = 8$ cm, since the increased residence time of the released volatiles in the bed favors the bursting of the bubbles

Table 2

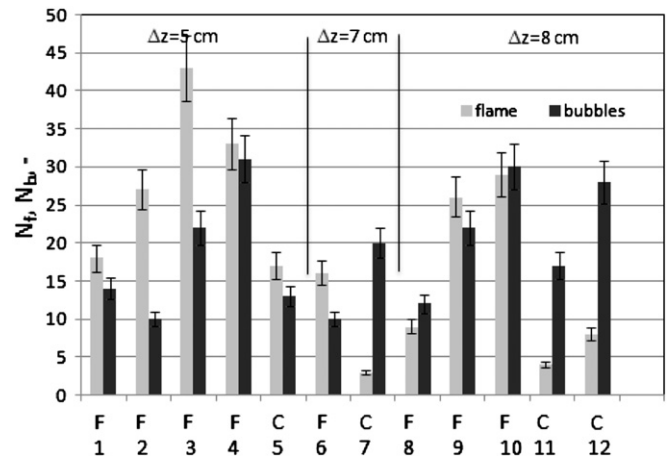
Number of events as determined by visual or software elaboration.

Δz , m	T, °C	Sand	N_f	N_b	N_e
spruce					
0.05	680	coarse			100
0.05	680	coarse			91
0.05	700	fine	18	14	32
0.05	700	fine	27	10	37
0.05	750	fine	43	22	65
0.05	750	fine	33	31	64
0.07	767	coarse			13
0.07	767	coarse			21
0.07	770	fine	58	15	73
0.07	770	fine	14	53	67
0.07	757	fine	3	20	23
0.08	680	coarse	4	17	21
0.08	680	coarse			24
0.08	700	fine			18
0.08	700	fine			23
0.08	780	fine			35
0.08	780	fine			34
beech					
0.05	670	coarse			97
0.05	670	coarse			103
0.05	700	fine	14	26	40
0.05	700	fine	13	26	39
0.05	750	fine			54
0.05	760	fine			44
0.08	680	coarse			19
0.08	680	coarse			13
0.08	700	fine	2	28	30
0.08	700	fine	18	5	23
0.08	780	fine	12	20	32
0.08	790	fine	21	22	43
GBC30					
0.07	765	coarse	13	0	13
0.07	765	coarse	12	0	12
0.07	760	fine			54
0.07	760	fine	26	24	50
0.07	760	fine	41	12	53
0.07	770	fine	41	15	56
PC30					
0.07	762	coarse	0	0	0
0.07	762	coarse	0	0	0
0.07	770	fine			17
0.07	770	fine	20	5	25
0.07	770	fine			23

grey shaded values obtained by visual elaboration

**Fig. 8.** Number of events as function of particle depth (A) and bed temperature (B); selected data from Table 2 for spruce pellets and beech rods.

before their eruption. Other interconnected dependencies are not easily understandable. For instance, increasing bed particle size leads to a partial reduction of bursting phenomena only at the largest Δz . It is worth recalling that when the particle is forced by the cage into a submerged position, the segregation mechanism of the volatiles via the formation of rising bubbles, is partly counter-balanced by the cross diffusion in the bed, whose extent mainly depends on the bed fluid-dynamics and temperature. In coarse bed, the gas leakage from a forming bubble to the emulsion phase is substantially higher since the permeability of the emulsion surface is proportional to the minimum fluidization

**Fig. 9.** Comparison between the numbers of flame and bubble events for spruce pellets (F: fine bed, C: coarse bed; T = 680–700 °C for 1, 2, 5, 6, 11, 12; T = 760–780 °C for 3, 4, 7–10).

velocity [18]; thus, a larger amount of volatiles is transferred from the endogenous bubble to the emulsion and the probability of bubble/flame events decreases. It is worth recalling that the gas diffusion coefficient increases on temperature with 3/2 power law [19], whereas the devolatilization rate is proportional on T , being controlled by the thermal exchange. Thus, a temperature increase should have a larger effect on the gas diffusion mechanism with respect to the devolatilization rate, resulting in a mitigation of the bursting events. However, these mechanisms become ineffective when the particle depth is too low and bubble residence time is very short. Furthermore, it is likely that larger bubbles are formed at higher devolatilization rate (i.e. higher T) also by coalescence, limiting the effectiveness of gas diffusion from the bubble as consequence of the decreased surface/volume ratio.

In order to correlate the experimental data with fuel and FB properties, the dimensionless group Φ is introduced, as reported in Eq. 1.

$$\Phi = \frac{V \cdot k_t / r_p \cdot d_s \cdot (T - T_d)}{100 \cdot \Delta H_d \cdot \Delta z^2 \rho_p \cdot D_g} \quad 1$$

Φ is based on:

the volatile content V (dry basis); the thermal conductivity k_t ; the fuel particle radius r_p ; the bed particle size d_s ; the vertical penetration of the fuel particle within the bed Δz ; the bed temperature T ; the devolatilization enthalpy ΔH_d and temperature T_d ; the fuel particle density ρ_p ; the gas diffusion coefficient D_g . ΔH_d was computed on the basis of the data reported in Table 1 for the fuel mixtures. The thermal conductivity was assumed to be equal to 0.18, 0.11 and 0.15 $\text{W m}^{-1} \text{K}^{-1}$ for beech rods, spruce pellets and wood-coal pellets, respectively.

Introducing the Biot number $Bi = h_p r_p / k_t$ [3] for the fuel particle, it results in the range 3–7, indicating a limiting action of the intra-particle thermal conduction and providing soundness for considering k_t in Eq. 1. The heat transfer coefficient in the fluidized bed ($h_p = 200 \div 250 \text{ W/m}^2\text{K}$) was calculated following Kunii and Levenspiel [12].

For the choice of the variables that appear in the group Φ some speculations were made, as reported hereinafter. The experimental findings suggest that the particle depth has a dominant role in determining bursting events for the influence on the bubble residence time; thus inversed square root dependence is postulated in Eq. 1. Of course, the volatile content of the fuel has a straightforward influence in determining bursting events, so a linear dependence is assumed. The variables that can promote (k_t , $T - T_d$) or hinder (r_p , ΔH_d , ρ_p) the heat-up of the pellet are reported in the numerator or denominator of Eq. 1, respectively. The gas diffusion coefficient, which promotes the mass transfer of the volatiles to the emulsion phase, is congruently reported in the denominator. The influence of bed particle size d_s is controversial since it has influence on both bed fluid dynamics and heat transfer coefficient.

The experimental data of N_e are plotted against Φ in Fig. 10. A linear interpolation is also proposed as reported in the figure, although the dispersion of the data is rather high ($R^2 = 0.36$). The correlation represents a novel attempt in order to provide an empirical link between the extent of volatile segregation and relevant fuel properties as well as FB variables. Fig. 11 displays the ratio between the number of bubble and flame events (N_b/N_f) as function of Φ for those points of Fig. 10 obtained by software elaboration. It clearly appears to be a decreasing trend of N_b/N_f with Φ , highlighted by the interpolation line, that is mainly due to the reduced particle depth and the consequent reduced residence time of the bubbles.

Altogether, the number of bursting bubbles is enhanced by the factors favoring the rapid release of volatiles such as the temperature difference and the thermal conductivity, whereas it is depressed by the factors contributing to disperse or mitigate the volatile segregation, first of all the depth at the which the fuel particle is held.

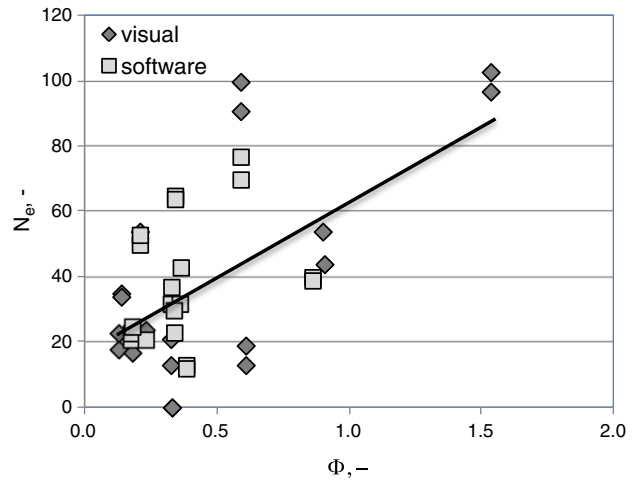


Fig. 10. Number of events as function of the dimensionless variable Φ .

4. Conclusions

The devolatilization behavior of fuel particles, and in particular pellets, was studied. In general, upon a short delay from pellet feeding, smoke/flames appeared during the entire devolatilization time, lasting dozens of seconds. In general, no primary fragmentation occurred during the devolatilization with both “free pellet” and “cage” technique.

The trend of the devolatilization time is consistent with the volatile content of the fuel (beech & spruce > GBC > PC), a longer t_{dev} being needed for complete devolatilization of pellets with larger volatile content. The pelletization appears to be also effective for improving the devolatilization time.

During devolatilization, two kinds of events can be distinguished: i) the eruption of a “hot bubble” produced by bursting a submerged fuel-rich bubble, ii) the generation of “flames” at the bed surface.

The tests proved that the segregation mechanism of the volatiles via the formation of rising bubbles, is partly counter-balanced by the cross diffusion in the bed. In particular the particle depth of the devolatilizing particle has the largest impact in decreasing the number of bursting phenomena. Coarse bed particle size also promotes the diffusion of the volatiles into the emulsion phase, reducing the observed bursting events.

By plotting the experimental data of N_e against a dimensionless variable Φ – function of FB and fuel properties – and by setting a linear interpolation, the number of “hot bubble” and “flame” events

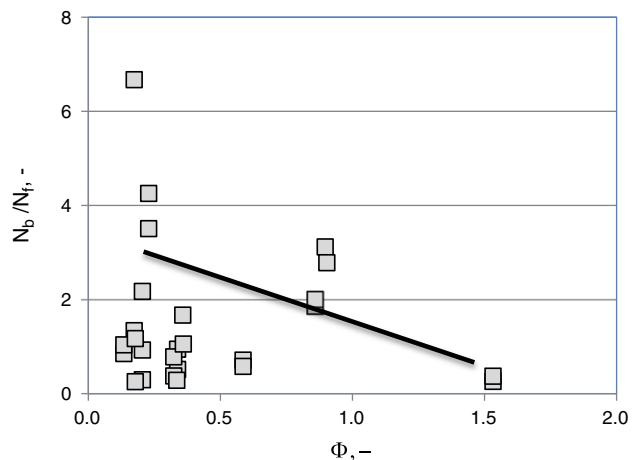


Fig. 11. Number of flame events as function of the dimensionless variable Φ (software elaboration).

results linearly dependent on the thermal conductivity, the volatile content, the bed temperature, and inversely dependent on the mass diffusion coefficient, the square of the depth in the bed, and the heat of pyrolysis/devolatilization. Some controversial dependencies, in particular on temperature and bed particle size, still exist and merit further investigation.

From a practical point of view, all factors forcing the pellets to remain submerged in the bed during the devolatilization or favoring the lateral dispersion of the volatiles are beneficial for reducing the bed bypass of the volatiles and enhancing the fuel conversion in the bed.

Nomenclature

Bi	biot number, -
d_s	particle size, m
D_g	mass diffusion coefficient, $m^2 s^{-1}$
h_p	heat transfer coefficient of fuel particles, $W m^{-2} K^{-1}$
k_t	thermal conductivity, $W m^{-1} K^{-1}$
N_b	number of “hot bubble” events, -
N_f	number of “flame” events, -
N_e	number of “flame” and “hot bubble” events, -
r_p	particle radius, m
t_{dev}	devolatilization time, s
T	bed temperature, °C
T_d	devolatilization temperature, °C
U	fluidization velocity, $m s^{-1}$
U_{mf}	minimum fluidization velocity, $m s^{-1}$
V	content of volatiles, %
Y	luminosity index, -

Greek symbols

ΔH_d	devolatilization enthalpy, $J kg^{-1}$
Φ	dimensionless variable, -
λ, λ_t	luminosity, -
ρ_p	particle density, $kg m^{-3}$
Δz	depth of the particle in the cage below bed level, m

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